

May Heavy hadrons of the 4th generation be hidden in our Universe while close to detection?

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Abstract

Metastable quarks of 4th generation are predicted in the framework of heterotic string phenomenology. Their presence in heavy stable hadrons are usually strongly constrained; however their *hidden* compositions in Heavy doubly charged baryons here considered are found to be still allowable: we studied their primordial quark production in the early Universe, their freezing into cosmic Heavy hadrons, their later annihilation into cosmic ray as well as their relic presence in our Universe and among us on Earth. We discuss also their possible production in present or future accelerators. Indeed if the lightest quarks and antiquarks of the 4th generation are stored in doubly charged baryons and neutral mesons, their lifetime can exceed the age of the Universe; the existence of such an anomalous Helium-like (and neutral Pion-like) stable particles may escape present experimental limits, while being close to present and future experimental test. On the contrary primordial abundance of lightest hadrons of the 4th generation with charge +1 can not decrease below the experimental upper limits on anomalous hydrogen and therefore (if stable) it is excluded. While 4th quark hadrons are rare, their presence may play different and surprising role in cosmic rays, muon and neutrino fluxes and cosmic electromagnetic spectra. Most of these traces are tiny, but nearly detectable.

Key words: cosmology, cosmic rays, 4th generation, anomalous helium

PACS: 98.80.Cq, 04.70.Bw, 04.70.Dy, 98.80.Hw(?)

1 Introduction

The problem of existence of quarks and leptons of 4th generation is among the most important in the modern high energy physics. The natural extension of the Standard model leads in the heterotic string phenomenology to the prediction of fourth generation of quarks and leptons [1,2] with a stable massive 4th neutrino [3,4,5,6]. The comparison between the rank of the unifying group E_6 ($r = 6$) and the rank of the Standard model ($r = 4$) implies the existence of new conserved charges and new (possibly strict) gauge symmetries. New strict gauge U(1) symmetry (similar to U(1) symmetry of electrodynamics) is possible, if it is ascribed to the fermions of 4th generation. This hypothesis explains the difference between the three known types of neutrinos and neutrino of 4th generation. The latter possesses new gauge charge and, being Dirac particle, can not have small Majorana mass due to see saw mechanism. If the 4th neu-

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trino is the lightest particle of the 4th quark-lepton family, strict conservation of the new charge makes massive 4th neutrino to be absolutely stable. Following this hypothesis [1] quarks and leptons of 4th generation are the source of new long range interaction, (which we'll call further y -interaction) similar to the electromagnetic interaction of ordinary charged particles.

Recent analysis [7] of precision data on the Standard model parameters has taken into account possible virtual contributions of 4th generation particles. It was shown that 4th quark-lepton generation is not excluded if 4th neutrino, being Dirac and (quasi-)stable, has a mass about 50 GeV (47-50 GeV is 1σ interval, 46.3-75 GeV is 2σ interval) [7] and other 4th generation fermions satisfy their direct experimental constrains (above 80-220 GeV). We will concentrate our attention here on given values of mass for 4th generation fermions, assuming that the mass of the lightest quark is about 250 GeV.

If the lightest quark Q of 4th generation possess new strictly conserved gauge charge, it can decay only to 4th generation leptons owing to GUT-type interactions, what makes it sufficiently long living. If its lifetime exceeds the age of the Universe, primordial Q -quark (and \bar{Q} -quark) hadrons should be present in the modern matter. If this lifetime is less than the age of the Universe, there should be no primordial 4th generation quarks, but they can be produced in cosmic ray interactions and be present in cosmic ray fluxes. The assumed masses for these quarks make their search a challenge for the present and future accelerators.

In principle, the composition of the lightest baryon of 4th generation can be: (Uuu) (charge $+2$)¹, (Uud) (charge $+1$), (Udd) (charge 0) or (if $m_D < m_U$) (Duu) (charge $+1$), (Dud) (charge 0), (Ddd) (charge -1) and the corresponding lightest mesons $(\bar{U}u)$ (charge 0), $(\bar{U}d)$ (charge -1) or $(\bar{D}u)$ (charge $+1$) and $(\bar{D}d)$ (charge 0). In the present paper we mainly follow the assumption that $m_D > m_U$, which excludes the baryon with the negative charge, while the lightest $(\bar{U}d)$ meson seems to be excluded by the quark model arguments. These arguments also exclude neutral (Udd) baryon as the lightest. It leaves theoretically favorable (Uud) and theoretically less favorable (Uuu) as only candidates for lightest baryon of 4th generation with the only possibility of neutral $(\bar{U}u)$ as the lightest meson.

We analyze the mechanisms of production of metastable Q (and \bar{Q}) hadrons in the early Universe, cosmic rays and accelerators and reveal the possible signatures of their existence. We'll show that though it may be more probable that the lightest hadron of the 4th generation has the charge $+1$ and Q -quark should have decay lifetime less than the age of the Universe to avoid the contradiction with the negative results of the anomalous hydrogen search,

¹ One can call this particle Δ_U^{++} .

the theoretically less favorable case of lightest (Uuu) baryon and ($\bar{U}u$) meson, mostly considered in the present paper, deserves special interest. Such doubly charged and neutral primordial hadrons can be sufficiently stable to be present in the modern Universe and still remain elusive for their direct searches. On the other hand the set of direct and indirect effects of their existence provides the test in cosmic ray and underground experiments which can be decisive for this hypothesis. In view of the interesting possibility revealed for Q -quark to be sufficiently stable we mainly use throughout the paper the examples, corresponding to the case, when U -quark of 4th generation is lighter than D -quark. However the calculations of primordial abundance, cosmic ray production and effects of heavy quark annihilation bear general character and are valid for any charge assignment for Q and its lightest hadrons.

In the next sections we consider U and \bar{U} hadrons presence since early Universe (Sec.2) up to their early freezing (details in App. 1-4) and later galactic clustering, their annihilation and survival (Sec.3, Appendix 5), their blowing wind onto Earth (Sec.4) and their further annihilation and relic presence in cosmic rays (sec.5), polluted matter, rarest upgoing muons and possible Heavy quark UHECR showers influence (App.5-8). We consider (Sec.6) possible Heavy quark signatures in Tevatron and LHC. In the final Section 7 we summarize our present study on the novel cosmic and astrophysical scenario on Heavy hadrons, possible hidden and stored just here among us.

2 Primordial U -hadrons from Big Bang Universe

In the early Universe at temperatures highly above their masses fermions of 4th generation were in thermodynamics equilibrium with relativistic plasma. Strict conservation of new gauge $U(1)$ charge (y -charge) implies y -charge symmetry of their distribution. When in the course of expansion the temperature T falls down below the mass of the lightest U -quark, m , equilibrium concentration of quark-antiquark pairs of 4th generation is given by

$$n_4 = g_4 \left(\frac{Tm}{2\pi} \right)^{3/2} \exp(-m/T), \quad (1)$$

where $g_4 = 6$ is the effective number of their spin degrees of freedom. We use the units $\hbar = c = k = 1$ throughout this paper.

At the freezing out temperature T_f the rate of expansion exceeds the rate of annihilation to gluons $U\bar{U} \rightarrow gg$ and $U\bar{U}$ pairs are frozen out. The frozen out concentration at $T \sim T_f \approx m/30$ (See Appendix 1) is given by

$$r_4 \approx 2.5 \cdot 10^{-14} \frac{m}{250 \text{ GeV}}. \quad (2)$$

Even this value of primordial concentration of U -quarks with the mass $m = 250\text{GeV}$ would lead to the contribution into the modern density, which is by an order of magnitude less, than the baryonic density, so that U -quarks can not play a significant dynamical role in the modern Universe. The actual value of primordial U -particle concentration should be much smaller due to radiative and hadronic recombination, which reduce the abundance of frozen out U -particles.

Radiation of mutually attracting y -charges of U and \bar{U} can lead to formation of $U\bar{U}$ systems bound by y -attraction, in which U and \bar{U} rapidly annihilate. The rate of this radiative binding is calculated in Appendix 2 and is given by

$$\langle\sigma v\rangle\approx 6\cdot 10^{-13}(\frac{\alpha}{1/30})^2(\frac{300K}{T})^{9/10}(\frac{250\text{GeV}}{m})^{11/10}\frac{cm^3}{s}. \quad (3)$$

The decrease of U -hadron abundance owing to $U\bar{U}$ recombination is governed by the equation

$$\frac{dr_4}{dt} = -r_4^2 \cdot s \cdot \langle\sigma v\rangle, \quad (4)$$

where s is the entropy density (see Appendix 1).

Its solution at $T_f > T$ (see Appendix 2) turns to be independent on the frozen out concentration (2) and is given by (see Appendix 2)

$$r_4 \approx 0.013 \left(\frac{m}{T_f}\right)^{1/10} \frac{m}{\alpha_y^2 m_{Pl}} \approx 4 \cdot 10^{-16} \frac{m}{250\text{GeV}} \left(\frac{30^{-1}}{\alpha_y}\right)^2, \quad (5)$$

where $\alpha_y \sim 1/30$ is the running constant of y -interaction.

After QCD phase transition at $T = T_{QCD} \approx 150\text{MeV}$ quarks of 4th generation combine with light quarks into U -hadrons. In baryon asymmetrical Universe only excessive valence quarks should enter such hadrons, so that U -baryons and \bar{U} -mesons are formed. The details of U - and \bar{U} -quark hadronization are discussed in Appendix 3 and following this discussion we consider further mainly doubly charged (Uuu) baryon and neutral $(\bar{U}u)$ meson².

² The total charge of (Uuu) and $(\bar{U}u)$ is +2, what looks like a net electric charge asymmetry of the Universe. However the net charge of the Universe is vanishing due to the presence of two corresponding excessive electrons. This pair of electrons compensates the positive charge of three light u quarks, and the mechanism of this compensation is provided by the usual generation of baryon (and lepton) asymmetry of the Universe.

As it was revealed in [1,2] in the collisions of such mesons and baryons recombination of U and \bar{U} into unstable ($U\bar{U}$) "charmonium -like" state can take place, thus successively reducing the U -hadron abundance. Hadronic recombination should take place even in the absence of long range y -interaction of U -particles. So, we give first the result without the account of radiative recombination induced by this interaction.

The uncertainties in the estimation of hadronic recombination rate are discussed in Appendix 4. The maximal estimation for the reaction rate of recombination $\langle\sigma v\rangle$ is given by

$$\langle\sigma v\rangle \sim \frac{1}{m_\pi^2} \approx 6 \cdot 10^{-16} \frac{\text{cm}^3}{\text{s}} \quad (6)$$

or by

$$\langle\sigma v\rangle \sim \frac{1}{m_\rho^2} \approx 2 \cdot 10^{-17} \frac{\text{cm}^3}{\text{s}}. \quad (7)$$

The minimal realistic estimation (See Appendix 4) gives

$$\langle\sigma v\rangle \approx 0.4 \cdot (T_{eff} m^3)^{-1/2} (3 + \log(T_{QCD}/T_{eff})), \quad (8)$$

where $T_{eff} = \max\{T, \alpha_y m_\pi\}$.

Solution of Eq.(4) for $\langle\sigma v\rangle$ from the Eq.(6) is given by

Case A

$$r_4 = \frac{r_0}{1 + r_0 \cdot \sqrt{\frac{\pi g_{QCD}}{45} \frac{m_{Pl}}{m_\pi} \frac{T_{QCD}}{m_\pi}}} \approx 1.0 \cdot 10^{-20} \quad (9)$$

and it is $(\frac{m_\rho}{m_\pi})^2 \sim 30$ times larger for $\langle\sigma v\rangle$ from the Eq.(7):

Case B

$$r_4 = \frac{r_0}{1 + r_0 \cdot \sqrt{\frac{\pi g_{QCD}}{45} \frac{m_{Pl}}{m_\rho} \frac{T_{QCD}}{m_\rho}}} \approx 3.0 \cdot 10^{-19}. \quad (10)$$

For the minimal estimation of recombination rate (8) the solution of Eq.(4) has the form

$$r_4 = \frac{r_0}{1 + r_0 2 \cdot \sqrt{\frac{\pi g_{QCD}}{45} \frac{m_{Pl}}{m} \sqrt{\frac{T_{QCD}}{m}}}} \approx 5 \cdot 10^{-16} \left(\frac{m}{250 \text{ GeV}}\right)^{3/2}, \quad (11)$$

where in all the cases r_0 is given by Eq.(2) and $g_{QCD} \approx 15$ (see Appendix 3). These solutions are independent on the actual initial value of $r_4 = r_0$, if before QCD phase transition it was of the order of (2). We neglect in our estimations possible effects of recombination in the intermediate period, when QCD phase transition proceeds.

With the account for radiative recombination it is the value (5) that should be taken at $T \sim T_{QCD}$ as r_0 in the solutions (9), (10) and (11) for the results of hadronic recombination. Such account does not change the values (9) and (10), which are still with the high accuracy independent on r_0 . However, for the minimal estimation of the recombination rate (8) the result of hadronic recombination is modified and reads

Case C

$$r_4 \approx 2 \cdot 10^{-16} \left(\frac{m}{250 GeV} \right)^{3/2}. \quad (12)$$

The existence of new massless U(1) gauge boson (y -photon) implies the presence of primordial thermal y -photon background in the Universe. Such background should be in equilibrium with ordinary plasma and radiation until the lightest particle bearing y -charge (4th neutrino) freezes out. For the accepted value of 4th neutrino mass ($\geq 50 GeV$) 4th neutrino freezing out and correspondingly decoupling of y -photons takes place before the QCD phase transition, when the total number of effective degrees of freedom is sufficiently large to suppress the effects of y -photon background in the period of Big Bang nucleosynthesis. This background does not interact with nucleons and does not influence the BBN reactions rate, while the suppression of y -photon energy density leads to insignificant effect in the speeding up cosmological expansion rate in the BBN period. In the framework of the present consideration the existence of primordial y -photons does not play any significant role in the successive evolution of U -hadrons.

In the period of recombination of nuclei with electrons charged U -baryons recombine with electrons to form atoms of anomalous isotopes. The substantial (up to 10 orders of magnitude) excess of electron number density over the number density of primordial U -baryons makes virtually all U -baryons to form atoms. The cosmological abundance of free charged U -baryons is to be exponentially small after recombination. If the lightest is (Uuu) baryon with electric charge +2, atoms of anomalous He are formed. U -hadrons with charge +1 form atoms of anomalous hydrogen.

These atoms, having atomic cross sections of interaction with matter, participate then in formation of astrophysical bodies, when galaxies are formed. One might assume that neutral U -hadrons, having nuclear interactions and being clustered in galaxies, should not follow matter in formation of stars and plan-

ets, and that one can expect suppression of their concentration in such bodies. However the existence of Coulomb-like y -attraction will make them to obey the condition of neutrality in respect to the y -charge. Therefore owing to neutrality condition the number densities of U - and \bar{U} -hadrons in astrophysical bodies should be equal³.

3 Evolution of U -hadron content in galactic matter

In the astrophysical body with atomic number density n the initial U -hadron abundance $n_{U0} = r_u \cdot n$ can decrease with time due to $U\bar{U}$ recombination. Under the neutrality condition

$$n_U = n_{\bar{U}}$$

the relative U -hadron abundance $r = n_U/n = n_{\bar{U}}/n$ is governed by the equation

$$\frac{dr}{dt} = -r^2 \cdot n \cdot \langle \sigma v \rangle. \quad (13)$$

The solution of this equation is given by

$$r = \frac{r_u}{1 + r_u \cdot n \cdot \langle \sigma v \rangle \cdot t}. \quad (14)$$

If

$$n \cdot \langle \sigma v \rangle \cdot t \gg \frac{1}{r_u}, \quad (15)$$

the solution (14) takes the form

$$r = \frac{1}{n \cdot \langle \sigma v \rangle \cdot t}. \quad (16)$$

³ In this sense there is a very remarkable and obvious difference between common (light-quark) baryon matter and the 4th quark matter: there is no room for any lepton-baryon asymmetry as in our matter. The same asymmetry leads to 250 times larger cosmological density for this matter, than for ordinary baryonic, what is by 10 times larger, than it is allowed for dark matter. The contradiction grows to 20 orders of magnitude, if we take into account the upper bounds on the presence of this matter around us.

and, being independent on the initial value, U -hadron abundance decreases inversely proportional to time.

By definition $r_u = f_i/A_{atom}$, where A_{atom} is the averaged atomic weight of the considered matter and f_i is the initial U -hadron to baryon ratio. In the pregalactic matter this ratio is determined by r_4 from A) Eq.(9), B) Eq.(10) and C) Eq.(12) and is equal to

$$f_4 = \frac{r_4}{r_b} = \begin{cases} 10^{-10} \text{ for the case A,} \\ 3 \cdot 10^{-9} \text{ for the case B,} \\ 2 \cdot 10^{-6} \text{ for the case C.} \end{cases} \quad (17)$$

Here $r_b \approx 10^{-10}$ is baryon to entropy ratio, defined in Eq.(40) in Appendix 3.

Taking for averaged atomic number density in the Earth $n \approx 10^{23} \text{ cm}^{-3}$, one finds that during the age of the Solar system primordial U -hadron abundance in the terrestrial matter should have been reduced down to $r \approx 10^{-28}$. One should expect similar reduction of U -hadron concentration in Sun and all the other old sufficiently dense astrophysical bodies. Therefore in our own body we might contain just one of such heavy hadrons. However, as shown later on in Section 4, the persistent pollution from the galactic gas nevertheless may increase this relic number density to a stationary much larger ($r \approx 10^{-23}$) value.

The principal possibility of strong reduction in dense bodies for primordial abundance of exotic charge symmetric particles due to their recombination in unstable charmonium like systems was first revealed in [13] for fractionally charged colorless composite particles (fractons).

The U -hadron abundance in the interstellar gas strongly depends on the matter evolution in Galaxy, which is still not known to the extent, we need for our discussion.

Indeed, in the opposite case of low density or of short time interval, when the condition (15) is not valid, namely, at

$$n < \frac{1}{r_u \langle \sigma v \rangle t} = A_{atom} \cdot \frac{T}{300K} \cdot \frac{t_U}{t} \text{ cm}^{-3} \begin{cases} 4 \cdot 10^4 \text{ for the case A,} \\ 10^3 \text{ for the case B,} \\ 2 \text{ for the case C,} \end{cases} \quad (18)$$

where $t_U = 4 \cdot 10^{17} \text{ s}$ is the age of the Universe, U -hadron abundance does not change its initial value.

In principle, if in the course of evolution matter in the forming Galaxy was present during sufficiently long period ($t \sim 10^9 \text{ yrs}$) within cold ($T \sim 10 \text{ K}$) clouds with density $n \sim 10^3 \text{ cm}^{-3}$ U -hadron abundance retains its primordial value for the cases A and B ($f_i = f_4$), but falls down $f_i = 5 \cdot 10^{-9}$ in the case C, making this case close to the case B. The above argument may not imply all the U -hadrons to be initially present in cold clouds. They can pass through cold clouds and decrease their abundance in the case C at the stage of thermal instability, when cooling gas clouds, before they become gravitationally bound, are bound by the external pressure of the hot gas. Owing to their large inertia heavy U -hadron atoms from the hot gas can penetrate much deeply inside the cloud and can be captured by it much more effectively, than ordinary atoms. Such mechanism can provide additional support for reduction of U -hadron abundance in the case C.

However, according to Appendix 7, in particular annihilation of U -hadrons leads to multiple γ production. If U -hadrons with relative abundance f_4 annihilate at the redshift z , it should leave in the modern Universe a background γ flux

$$F(E > E_\gamma) = \frac{N_\gamma \cdot f_4 \cdot r_b \cdot n_{\gamma \text{ mod}} \cdot c}{4\pi} \approx 3 \cdot 10^3 f_4 (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1},$$

of γ quanta with energies $E > E_\gamma = 10 \text{ GeV}/(1+z)$. Here $n_{\gamma \text{ mod}} \approx 400 \text{ cm}^{-3}$ is the modern number density of relic photons and the numerical values for γ multiplicity N_γ are given in table 1 of Appendix 7. So annihilation even as early as at $z \sim 9$ leads in the case C to the contribution into diffuse extragalactic gamma emission, exceeding the flux, measured by EGRET by three orders of magnitude. The latter can be approximated as

$$F(E > E_\gamma) \approx 3 \cdot 10^{-6} \left(\frac{E_0}{E_\gamma} \right)^{1.1} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1},$$

where $E_0 = 451 \text{ MeV}$.

The above upper bound strongly restricts ($f_4 \leq 10^{-9}$ the earliest abundance because of the consequent impossibility to reduce the primordial U -hadron abundance by U -hadron annihilation in low density objects. In the cases A and B annihilation in such objects should not take place, whereas annihilation within the dense objects, being opaque for γ radiation, can avoid this constraint due to strong suppression of outgoing γ flux. However, such constraint nevertheless should arise for the period of dense objects' formation. For example, in the course of protostellar collapse hydrodynamical timescale $t_H \sim 1/\sqrt{\pi G \rho} \sim 10^{15} \text{ s}/\sqrt{n}$ exceeds the annihilation timescale

$$t_{an} \sim \frac{1}{f_4 n \langle \sigma v \rangle} \sim \frac{10^{12} \text{ s}}{f_4 n} \left(\frac{1/30}{\alpha} \right)^2 \left(\frac{T}{300 \text{ K}} \right)^{9/10} \left(\frac{m}{250 \text{ GeV}} \right)^{11/10}$$

at $n > 10^{14} \left(\frac{10^{-10}}{f_4}\right)^2 \left(\frac{1/30}{\alpha}\right)^4 \left(\frac{T}{300K}\right)^{9/5} \left(\frac{m}{250GeV}\right)^{11/5}$, where n is in cm^{-3} . We consider homogeneous cloud with mass M has radius $R \approx \frac{10^{19}cm}{n^{1/3}} \left(\frac{M}{M_\odot}\right)^{1/3}$, where $M_\odot = 2 \cdot 10^{33}g$ is the Solar mass. It becomes opaque for γ radiation, when this radius exceeds the mean free path $l_\gamma \sim 10^{26}cm/n$ at $n > 3 \cdot 10^{10}cm \left(\frac{M}{M_\odot}\right)^{1/2}$. As a result, for f_4 as large as in the case C, rapid annihilation takes place when the collapsing matter is transparent for γ radiation and the EGRET constraint can not be avoided. The cases A and B are consistent with this constraint.

Note that at $f_4 < 5 \cdot 10^{-6} \left(\frac{M}{M_\odot}\right)^{2/9}$, i.e. for all the considered cases energy release from U -hadron annihilation does not exceed the gravitational binding energy of the collapsing body. Therefore, U -hadron annihilation can not prevent the formation of dense objects but it can provide additional energy source, e.g. at early stages of evolution of first stars. Its burning is quite fast (few years) and its luminosity may be quite extreme, leading to a short inhibition of star formation.

According to above arguments U -baryon abundance in the primary cosmic rays can be close to the primordial value f_4 . It gives for case B

$$f_4 = \frac{r_4}{r_b} \sim 3 \cdot 10^{-9}. \quad (19)$$

If (Uuu) is the lightest U -baryon, its fraction in cosmic ray helium component can reach in this case the value

$$\frac{(Uuu)}{{}^4He} \sim 3 \cdot 10^{-8},$$

which is accessible for future cosmic rays experiments, such as RIM-PAMELA and AMS 02 on International Space Station.

Similar argument in the case C would give for this fraction $\sim 2 \cdot 10^{-5}$, what may be already excluded by the existing data. However, it should be noted that the above estimation assumes significant contribution of particles from interstellar matter to cosmic rays. If cosmic ray particles are dominantly originated from the purely stellar matter, the decrease of U -hadron abundance in stars would substantially reduce the primary U -baryon fraction of cosmic rays.

4 Galactic blowing of U -baryon atoms polluting our Earth

Since the condition Eq.(18) is valid for the disc interstellar gas, having the number density $n_g \sim 1cm^{-3}$ one can expect that the U -hadron abundance in it can decrease relative to the primordial value only due to enrichment of this

gas by the matter, which has passed through stars and had the suppressed U -hadron abundance according to Eq.(16). Taking the factor of such decrease of the order of the ratio of total masses of gas and stars in Galaxy $f_g \sim 10^{-2}$ and accounting for the acceleration of the interstellar gas by Solar gravitational force, so that the infalling gas has velocity $v_g \approx 4.2 \cdot 10^6 \text{cm/s}$ in vicinity of Earth's orbit, one obtains that the flux of U -hadrons coming with interstellar gas should be of the order of

$$I_U = \frac{f_4 f_g n_g v_g}{8\pi} \approx 1.5 \cdot 10^{-7} \frac{f_4}{10^{-10}} (cm^2 \cdot s \cdot ster)^{-1}, \quad (20)$$

where f_4 is given by the Eq.(17).

Presence of primordial U -hadrons in the Universe should be reflected by their existence in Earth's atmosphere and ground. However, according to Eq.(16) (see discussion in Section 3) primordial terrestrial U -hadron content should strongly decrease due to radiative recombination, so that the U -hadron abundance in Earth is determined by the kinetic equilibrium between the incoming U -hadron flux and the rate of decrease of this abundance by different mechanisms.

In the successive analysis we'll concentrate our attention on the case, when the lightest U baryon is doubly charged (Uuu) and the lightest \bar{U} meson is electrically neutral ($\bar{U}u$). In this case U baryons look like superheavy anomalous helium isotopes.

Searches for anomalous helium were performed in series of experiments based on accelerator search [14], spectrometry technique [15] and laser spectroscopy [16]. From the experimental point of view an anomalous helium represents a favorable case, since it remains in the atmosphere whereas a normal helium is severely depleted in the terrestrial environment due to its light mass.

The best upper limits on the anomalous helium were obtained in [16]. It was found by searching for a heavy helium isotope in the Earth's atmosphere that in the mass range 5 GeV - 10000 GeV the terrestrial abundance (the ratio of anomalous helium number to the total number of atoms in the Earth) of anomalous helium is less than $3 \cdot 10^{-19} - 2 \cdot 10^{-19}$. The search in the atmosphere is reasonable because heavy gases are well mixed up to 80 km and because the heavy helium does not sink due to gravity deeply in the Earth and is homogeneously redistributed in the volume of the World Ocean at the timescale of 10^3yr .

The kinetic equations, describing evolution of anomalous helium and U -mesons in matter have the form

$$\frac{dn_U}{dt} = j_U - n_U \cdot n_{\bar{U}} \cdot \langle \sigma v \rangle - j_{gU} \quad (21)$$

for U -meson number density n and

$$\frac{dn_{\bar{U}}}{dt} = j_{\bar{U}} - n_{\bar{U}} \cdot n_U \cdot \langle \sigma v \rangle - j_{g\bar{U}} \quad (22)$$

for number density of anomalous helium n_U . Here j_U and $j_{\bar{U}}$ take into account the income of, correspondingly, U -baryons and U -mesons to considered region, the second terms on the right-hand-side of equations describe $U\bar{U}$ recombination and the terms j_{gU} and $j_{g\bar{U}}$ determine various mechanisms for outgoing fluxes, e.g. gravitationally driven sink of particles. The latter effect is much stronger for U -mesons due to much lower mobility of U -baryon atoms. However, long range Coulomb like interaction prevents them from sinking, provided that its force exceeds the Earth's gravitational force.

In order to compare these forces let's consider the World's Ocean as a thin shell of thickness $L \approx 4 \cdot 10^5 \text{ cm}$ with homogeneously distributed y charge, determined by distribution of U -baryon atoms with concentration n . The y -field outside this shell according to Gauss' law is determined by

$$2E_y S = 4\pi e_y n S L,$$

being equal to

$$E_y = 2\pi e_y n L.$$

In the result y force, exerting on \bar{U} -mesons

$$F_y = e_y E_y,$$

exceeds gravitational force for U -baryon atom concentration

$$n > 10^{-7} \frac{m}{250 \text{ GeV}} \left(\frac{30^{-1}}{\alpha_y} \right) \text{ cm}^{-3}. \quad (23)$$

Note that the mobility of U -baryon atoms and \bar{U} mesons differs by 10 order of magnitude, what can lead to appearance of excessive y -charges within the limits of (23). One can expect that such excessive charges arise due to the effective slowing down of U -baryon atoms in high altitude levels of Earth's atmosphere, which are transparent for \bar{U} mesons, as well as due to the 3 order of magnitude decrease of \bar{U} mesons when they enter the Earth's surface.

Under the condition of neutrality, which is strongly protected by Coulomb-like y -interaction, all the corresponding parameters for \bar{U} -mesons and U -baryons in the Eqs.(21)-(22) are equal, if Eq.(23) is valid. Provided that the timescale of mass exchange between the Ocean and atmosphere is much less than the timescale of sinking, sink terms can be neglected.

The stationary solution of Eqs.(21)-(22) gives in this case

$$n = \sqrt{\frac{j}{\langle \sigma v \rangle}}, \quad (24)$$

where

$$j_U = j_{\bar{U}} = j \sim \frac{2\pi I_U}{L} = 10^{-12} \frac{f_4}{10^{-10}} cm^{-3} s^{-1} \quad (25)$$

and $\langle \sigma v \rangle$ is given by the Eq.(3). For $j \leq 10^{-12} \frac{f_4}{10^{-10}} cm^{-3} s^{-1}$ and $\langle \sigma v \rangle$ given by Eq.(3) one obtains in water

$$n \leq \sqrt{\frac{f_4}{10^{-10}}} cm^{-3}.$$

It corresponds to terrestrial U -baryon abundance

$$r \leq 10^{-23} \sqrt{\frac{f_4}{10^{-10}}},$$

being below the above mentioned experimental upper limits for anomalous helium ($r < 10^{-19}$) even for the case C with $f_4 = 2 \cdot 10^{-6}$. In air one has

$$n \leq 10^{-3} \sqrt{\frac{f_4}{10^{-10}}} cm^{-3}.$$

For example in a cubic room of 3m size there are nearly 27 thousand heavy hadrons.

Note that putting formally in the Eq.(24) the value of $\langle \sigma v \rangle$ given by the Eq.(6) one obtains $n \leq 6 \cdot 10^2 cm^{-3}$ and $r \leq 6 \cdot 10^{-20}$, being still below the experimental upper limits for anomalous helium abundance. So the qualitative conclusion that recombination in dense matter can provide the sufficient decrease of this abundance avoiding the contradiction with the experimental constrains could be valid even in the absence of gauge y -charge and Coulomb-like y -field interaction for U -hadrons. It looks like the hadronic recombination alone can be sufficiently effective in such decrease. However, if we take the value of $\langle \sigma v \rangle$ given by the Eq.(7) one obtains n by the factor of $\frac{m_\rho}{m_\pi} \sim 5.5$ larger and $r \leq 3.3 \cdot 10^{-19}$, what exceeds the experimental upper limits for anomalous

helium abundance. Moreover, in the absence of y -attraction there is no dynamical mechanism, making the number densities of U -baryons and \bar{U} -mesons equal each other with high accuracy. So nothing seems to prevent in this case selecting and segregating U -baryons from \bar{U} -mesons. Such segregation, being highly probable due to the large difference in the mobility of U -baryon atoms and \bar{U} mesons can lead to uncompensated excess of anomalous helium in the Earth, coming into contradiction with the experimental constrains.

Similar result can be obtained for any planet, having atmosphere and Ocean, in which effective mass exchange between atmosphere and Ocean takes place. There is no such mass exchange in planets without atmosphere and Ocean (e.g. in Moon) and U -hadron abundance in such planets is determined by the interplay of effects of incoming interstellar gas, $U\bar{U}$ recombination and slow sinking of U -hadrons to the centers of planets. (See Appendix 6)

5 Correlation between cosmic ray and large volume underground detectors' effects

Inside large volume underground detectors (as Super Kamiokande) and in their vicinity U -hadron recombination should cause specific events ("spherical" energy release with zero total momentum or "wide cone" energy release with small total momentum), which could be clearly distinguished from the (energy release with high total momentum within "narrow cone") effects of common atmospheric neutrino - nucleon-lepton chain (as well as of hypothetical WIMP annihilation in Sun and Earth).

The absence of such events inside 22 kilotons of water in Super Kamiokande (SK) detector during 5 years of its operation would give the most severe constraint

$$n < 10^{-3} cm^{-3},$$

corresponding to $r < 10^{-26}$. For the considered type of anomalous helium such constraint would be by 7 order of magnitude stronger, than the results of present direct searches and 3 orders above our estimation in previous Section.

However, this constraint assumes that distilled water in SK does still contain polluted heavy hadrons (as it may be untrue). Nevertheless even for pure water it may not be the case for the detector's container and its vicinity. The conservative limit follows from the condition that the rate of U -hadron recombination in the body of detector does not exceed the rate of processes, induced by atmospheric muons and neutrinos. The presence of clustered-like muons originated on the SK walls would be probably observed. The possibility to detect upgoing muon signal from U -hadron recombination in atmosphere is considered in Appendix 8.

High sensitivity of large volume detectors to the effects of U -hadron recombination together with the expected increase of volumes of such detectors up to $1km^3$ offer the possibility of correlated search for cosmic ray U -hadrons and for effects of their recombination.

During one year of operation a $1km^3$ detector could be sensitive to effects of recombination at the U -hadron number density $n \approx 7 \cdot 10^{-6}cm^{-3}$ and $r \approx 7 \cdot 10^{-29}$, covering the whole possible range of these parameters, since this level of sensitivity corresponds to the residual concentration of primordial U -hadrons, which can survive inside the Earth. The income of cosmic U -hadrons and equilibrium between this income and recombination should lead to increase of effect, expected in large volume detectors.

Even, if the income of anomalous helium with interstellar gas is completely suppressed, pollution of Earth by U -hadrons from primary cosmic rays is possible. The minimal effect of pollution by U -hadron primary cosmic rays flux I_U corresponds to the rate of increase of U -hadron number density $j \sim \frac{2\pi I_U}{R_E}$, where $R_E \approx 6 \cdot 10^8 cm$ is the Earth's radius. If incoming cosmic rays doubly charged U -baryons after their slowing down in matter recombine with electrons we should take instead of R_E the Ocean's thickness $L \approx 4 \cdot 10^5 cm$ that increases by 3 orders of magnitude the minimal flux and the minimal number of events, estimated below. Equilibrium between this income rate and the rate of recombination should lead to $N \sim jVt$ events of recombination inside the detector with volume V during its operation time t .

For the minimal flux of cosmic ray U -hadrons, accessible to AMS 02 experiment during 3 years of its operation ($I_{min} \sim 10^{-9}I_\alpha \sim 4 \cdot 10^{-11}I(E)$, where $I(E)$ is given by Eq.(50), in the range of energy per nucleon $1 < E < 10GeV$) the minimal number of events expected in detector of volume V during time t is given by $N_{min} \sim \frac{2\pi I_{min}}{R_E}Vt$. It gives about 3 events per 10 years in SuperKamiokande ($V = 2.2 \cdot 10^{10}cm^3$) and about 10^4 events in the $1km^3$ detector during one year of its operation. The noise of this rate is one order and half below the expected influence of atmospheric ν_μ .

The possibility of such correlation facilitates the search for anomalous helium in cosmic rays and for the effects of U -hadron recombination in the large volume detectors.

The previous discussion assumed the lifetime of U -quarks τ exceeding the age of the Universe t_U . In the opposite case $\tau < t_U$ all the primordial U hadrons should decay to the present time and the cosmic ray interaction may be the only source of cosmic and terrestrial U hadrons (see Appendix 9).

6 Signatures for U -hadrons in accelerator experiments

The assumed value of U -quark mass makes the problem of its search at accelerators similar to the case of t -quark. However, the strategy of such search should take into account the principal difference from the case of unstable top quark. One should expect that in the considered case a stable hadron should be produced.

If these hadrons are neutral and doubly charged, as we dominantly considered above, the last ones can be observed as the 'disagreement' between the track curvature (3-momentum)

$$p = 0.3B \cdot R \cdot Q, \quad (26)$$

where B is magnetic field in T , p is momentum in GeV, R is radius of curvature in meters, Q is the charge of U hadrons in the units of elementary charge e , and the energy of the track measured in the calorimeter (or energy loss dE/dx). The search for such tracks at the Tevatron is highly desirable. The expected inclusive cross section of U -meson production at the Tevatron is about 0.7 pb (for $M_Q = 250$ GeV) and about 0.05 pb for the double charged barion (in the case of U -quark); more than a half of the events contains two non-relativistic heavy particles with the velocity $\beta < 0.7$.

The argument favoring (Uuu) as the lightest U baryon is simply based on the mass ratio of current u and d quarks. On the other hand there is an argument in favor of the fact that the Uud baryon must be lighter than the Uuu one. Indeed, in all models the scalar-isoscalar ud -diquark is lighter than the vector-isovector uu -diquark. One example is the model with the effective t'Hooft instanton induced four quark interaction, which provides a rather strong attraction in the scalar ud -channel and which is absent in the vector uu channel. In a more general form we can say that the interaction in isoscalar channel (isoscalar potential) must be stronger than that in the isovector case. Otherwise we will obtain a negative cross section for one or another reaction since the isovector interaction changes the sign under the replacement of d -quark by the u -quark.

Thus it is very likely that the Uuu -baryon will be unstable under the decay $(Uuu) \rightarrow (Uud) + \pi^+$. This expectation is confirmed by the properties of the charmed baryons (where the charm quark is much heavier than two other quarks). Indeed, the branching of the $\Sigma_c \rightarrow \Lambda_c + \pi$ decay is about 100% [20].

The uncertainty in the choice of the lightest baryon of the 4th generation is accomplished by the uncertainty of the choice of the lightest quark, is it U -quark in the analogy with the first generation, or D -quark, as it follows from the analogy with second and third generations. These ambiguities in

theoretical expectations make us to stipulate the signatures for 4th generation in accelerator searches, which are independent of the above mentioned uncertainties.

The expected cross section of the charge 1 heavy meson (like $U\bar{d}$) production is not too small. It is comparable with the t -quark cross section, depending on the mass of heavy quark. At the moment the best limits on the quarks of 4-th generation was given by the CDF collaboration using the dE/dx measurements. For the quark with electric charge $q = 2/3$ the limit is $M_U > 220$ GeV [21]. Therefore in the present paper we choose for our estimates the value $M_U = 250$ GeV, which corresponds to the production cross section of the order of 1 pb at the Tevatron energy⁴.

Due to a very large mass (more than 150 GeV) the new heavy hadrons are rather slow. About half of the yield is given by particles with the velocity $\beta < 0.7$. To identify such hadrons one may study the events with a large transverse energy (say, using the trigger - $E_T > 30$ GeV). The signature for a new heavy hadrons will be the 'disagreement' between the values of the full energy $E = \sqrt{m^2 + |\vec{p}|^2} - m$ measured in the calorimeter, the curvature of the track (which, due to a larger momentum $|\vec{p}| = E/\beta$, will be smaller than that for the light hadron where $E \simeq |p|$) and the energy loss dE/dx . For the case of heavy hadrons due to a low β the energy loss $\frac{dE^{QED}}{dx}$ caused by the electromagnetic interaction is larger than that for the ultrarelativistic light hadron, while in "hadron calorimeter" the energy loss caused by the strong interactions is smaller (than for a usual light hadron), due to a lower inelastic cross section for a smaller size heavy hadron, like $(U\bar{d})$ meson. Besides this the whole large E_T will be produced by the single isolated track and not by a usual hadronic jet, since the expected energy of the accompanying light hadrons $E_T^{acc} \sim \frac{1 \text{ GeV}}{m} E_T$ is rather low.

Another possibility to identify the new stable heavy hadrons is to use the Cherenkov counter or the time-of-flight information.

We hope that the hadrons, which contain a heavy quark of 4-th generation, may be observed in the new data collected during the RunII at the Tevatron and then at the LHC, or the limits on the mass of such a heavy quarks will be improved⁵.

⁴ The probability to recombine with diquark and to form the baryon is about order of magnitude lower.

⁵ If the mass of Higgs boson exceeds $2m$, its decay channel the pair of stable $Q\bar{Q}$ will dominate over the $t\bar{t}$, $2W$, $2Z$ and invisible channel to neutrino pair of 4th generation [22]. It may be important for the strategy of heavy Higgs searches.

7 Discussion

To conclude, the existence of hidden stable or metastable quark of 4th generation can be compatible with the severe experimental constraints on the abundance of anomalous isotopes in Earth's atmosphere and ground and in cosmic rays, even if the lifetime of such quark exceeds the age of the Universe. Though the primordial abundance $r = r_4/r_b$ of hadrons, containing such quark (and antiquark) can be hardly less than $r \sim 10^{-10}$, their primordial content can strongly decrease in dense astrophysical objects (in the Earth, in particular) owing to the process of recombination, in which hadron, containing quark, and hadron, containing antiquark, produce unstable charmonium-like quark-antiquark state.

To make such decrease effective, the equal number density of quark- and antiquark-containing hadrons should be preserved. It appeals to a dynamical mechanism, preventing segregation of quark- and antiquark-containing hadrons. Such mechanism, simultaneously providing strict charge symmetry of quarks and antiquarks, naturally arises, if the 4th generation possesses new strictly conserved $U(1)$ gauge (y -) charge. Coulomb-like y -charge long range force between quarks and antiquarks naturally preserves equal number densities for corresponding hadrons and dynamically supports the condition of y -charge neutrality.

It was shown in the present paper that if U -quark is the lightest quark of the 4th generation, and the lightest U -hadrons are doubly charged (Uuu)-baryon and electrically neutral ($\bar{U}u$)-meson, the predicted abundance of anomalous helium in Earth's atmosphere and ground as well as in cosmic rays is below the existing experimental constraints but can be within the reach for the experimental search in future. The whole cosmic astrophysics and present history of these relics are puzzling and surprising, but nearly escaping all present bounds.

Searches for anomalous isotopes in cosmic rays and at accelerators were performed during last years. Stable doubly charged U baryons offer challenge for cosmic ray and accelerator experimental search as well as for increase of sensitivity in searches for anomalous helium. In particular, they seem to be of evident interest for cosmic ray experiments, such as PAMELA and AMS02. $+2$ charged U baryons represent the low Z/A anomalous helium component of cosmic rays, whereas -2 charged \bar{U} baryons look like anomalous antihelium nuclei. However, in the baryon asymmetrical Universe the predicted amount of primordial \bar{U} baryons is exponentially small, whereas their secondary fluxes originated from cosmic ray interaction with the galactic matter are predicted at the level, few orders of magnitude below the expected sensitivity of future cosmic ray experiments. The same is true for cosmic ray $+2$ charged U baryons, if U -quark lifetime is less than the age of the Universe and primordial

U baryons do not survive to the present time.

The arguments for the lightest (Uuu)-baryon simply use the u and d current quark mass ratio. These arguments are not supported by models of quark interactions, which favor isoscalar (Uud) baryon to be the lightest among the 4th generation hadrons (provided that U quark is lighter, than D quark, what also may not be the case). If the lightest U -hadrons have electric charge $+1$ and survive to the present time, their abundance in Earth would exceed the experimental constraint on anomalous hydrogen. This may be rather general case for the lightest hadrons of the 4th generation. To avoid this problem of anomalous hydrogen overproduction the lightest quark of the 4th generation should have the lifetime, less than the age of the Universe.

However short-living are these quarks on the cosmological timescale in a very wide range of lifetimes they should behave as stable in accelerator experiments⁶.

With all the uncertainties in the predicted mass spectrum of 4th generation hadrons one can expect the cross section of their production to be at the level of the t -quark cross section. Stability of lightest hadrons and their large mass of about 250 GeV should make them rather slow. It offers a chance to use as their possible signature the "disagreement" between the total energy, measured in calorimeter, on one side, and curvature, single-particle character of track and energy loss, on the other side, in the events with large transverse energy at Tevatron and LHC.

In the present work we studied effects of 4th generation having restricted our analysis by the processes with 4th generation quarks and antiquarks. However, as we have mentioned in the Introduction in the considered approach absolutely stable neutrino of 4th generation with mass about 50 GeV also bears y -charge. The selfconsistent treatment of the cosmological evolution and astrophysical effects of y -charge plasma of neutrinos, antineutrinos, quarks and antiquarks of 4th generation will be the subject of special studies.

We believe that a tiny trace of heavy hadrons as anomalous helium and stable neutral meson⁷ may be hidden at a low level in our Universe ($\frac{n_U}{n_b} \sim 10^{-10} - 10^{-9}$) and even at much lower level here in our terrestrial matter a density $\frac{n_U}{n_b} \sim 10^{-23}$. There are good reasons to bound the 4th quark mass below TeV

⁶ With an intermediate scale of about 10^{11} GeV (as in supersymmetry models [25]) the expected lifetime of U -(or D -) quark $\sim 10^6$ years is much less than the age of the Universe but such quark is practically stable in any collider experiments.

⁷ Storing these charged and neutral heavy hadrons in the matter might influence its e/m properties, leading to the appearance of apparent fractional charge effect in solid matter. The present sensitivity for such effect in metals ranges from 10^{-22} to 10^{-20} .

energy. Therefore the mass window and relic density is quite narrow and well defined, open to a final test.

Acknowledgements

The work of K.B., M.Kh. and K.S. was performed in the framework of the State Contract 40.022.1.1.1106 and was partially supported by the RFBR grants 02-02-17490, 04-02-16073 and grant UR.02.01.008. (Univer. of Russia). M.Kh. expresses his gratitude to Abdus Salam International Centre for Theoretical Physics for hospitality.

Appendix 1. Freezing out of U -quarks

The expansion rate of the Universe is given by the expression

$$H = \sqrt{\frac{4\pi^3 g_{tot}}{45}} \frac{T^2}{m_{Pl}} \approx 1.66 g_{tot}^{1/2} \frac{T^2}{m_{Pl}}, \quad (27)$$

which follows from the expression for critical density of the Universe

$$\rho_{crit} = \frac{3H^2}{8\pi G} = g_{tot} \frac{\pi^2}{30} T^4.$$

When it starts to exceed the rate of quark-antiquark annihilation

$$R_{ann} = n_4 \langle \sigma v \rangle, \quad (28)$$

in the period, corresponding to $T = T_f < m$, quarks of 4th generation freeze out, so that their relative concentration

$$r_4 = \frac{n_4}{s} \quad (29)$$

does not follow the equilibrium distribution at $T < T_f$. Here the entropy density of the Universe on the RD stage is given by

$$s = \frac{\rho + p}{T} = \frac{4}{3} \frac{\rho}{T} = \frac{2\pi^2 g_{tot}}{45} T^3 \approx 0.44 g_{tot} T^3. \quad (30)$$

The entropy density can be conveniently expressed in terms of the number density $n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3$ of thermal photons as follows

$$s = \frac{\pi^4 g_{tot s}}{45\zeta(3)} n_\gamma \approx 1.80 g_{tot s} n_\gamma. \quad (31)$$

Under the condition of entropy conservation in the Universe, the number density of the frozen out particles can be simply found for any epoch through the corresponding thermal photon number density n_γ . Factors g_{tot} and $g_{tot s}$ take into account the contribution of all particle species and are defined as

$$g_{tot} = \sum_{bosons} g_{bos} \left(\frac{T_{bos}}{T} \right)^4 + \frac{7}{8} \sum_{fermions} g_{fer} \left(\frac{T_{fer}}{T} \right)^4$$

and

$$g_{tot s} = \sum_{bosons} g_{bos} \left(\frac{T_{bos}}{T} \right)^3 + \frac{7}{8} \sum_{fermions} g_{fer} \left(\frac{T_{fer}}{T} \right)^3,$$

where g_{bos} and g_{fer} is the number of spin degrees of freedom for bosons and fermions, respectively.

From the equality of the expressions Eq.(27) and Eq.(28) one gets

$$m/T_f \approx 42 + \ln(g_{tot}^{-1/2} m_p m \langle \sigma v \rangle)$$

with m_p being the proton mass and obtains, taking $\langle \sigma v \rangle \sim \frac{\alpha_{QCD}^2}{m^2}$ and $g_{tot}(T_f) = g_{tot s}(T_f) = g_f \approx 80 - 90$,

$$T_f \approx m/30$$

and

$$r_4 = \frac{H_f}{s_f \langle \sigma v \rangle} \approx \frac{4}{g_f^{1/2} m_{Pl} T_f \langle \sigma v \rangle} \approx 2.5 \cdot 10^{-14} \frac{m}{250 \text{ GeV}}. \quad (32)$$

Index "f" means everywhere that the corresponding quantity is taken at $T = T_f$. Also it is worth to emphasize, that given estimation for r_4 relates to only 4th quark or 4th antiquark abundances, assumed to be equal to each other.

The modern number density of frozen out particles can be found from this estimation as

$$n_{mod} = r_4 \cdot s_{mod}.$$

The modern entropy density s_{mod} is assumed to be determined by relic photons with temperature T and light neutrinos with temperature $T_\nu = (4/11)^{1/3} T$. It gives $g_{tot s mod} = 43/11$ and $s_{mod} = 7.04 \cdot n_{\gamma mod}$.

Note that if $T_f > \Delta = m_D - m$, where m_D is the mass of D -quark (assumed to be heavier, than U -quark) the frozen out concentration of 4th generation

quarks represent at $T_f > T > \Delta$ a mixture of nearly equal amounts of $U\bar{U}$ and $D\bar{D}$ pairs.

At $T < \Delta$ the equilibrium ratio

$$\frac{D}{U} \propto \exp\left(-\frac{\Delta}{T}\right)$$

is supported by weak interaction, provided that β -transitions ($U \rightarrow D$) and ($D \rightarrow U$) are in equilibrium. The lifetime of D -quarks, τ , is also determined by the rate of weak ($D \rightarrow U$) transition, and at $t \gg \tau$ all the frozen out $D\bar{D}$ pairs should decay to $U\bar{U}$ pairs.

Appendix 2. Radiative recombination

Radiative $U\bar{U}$ recombination is induced by "Coulomb-like" attraction of U and \bar{U} due to their y -interaction. It can be described in the analogy to the process of free monopole-antimonopole annihilation considered in [9]. Potential energy of Coulomb-like interaction between U and \bar{U} exceeds their thermal energy T at the distance

$$d_0 = \frac{\alpha}{T}.$$

In the case of y -interaction its running constant $\alpha = \alpha_y \sim 1/30$ [1]. For $\alpha \ll 1$, on the contrary to the case of monopoles [9] with $g^2/4\pi \gg 1$, the mean free path of multiple scattering in plasma is given by

$$\lambda = (n\sigma)^{-1} \sim (T^3 \cdot \frac{\alpha^2}{Tm})^{-1} \sim \frac{m}{\alpha^3 T} \cdot d_0,$$

being $\lambda \gg d_0$ for all $T < m$. So the diffusion approximation [9] is not valid for our case. Therefore radiative capture of free U and \bar{U} particles should be considered. According to [9], following the classical solution of energy loss due to radiation, converting infinite motion to finite, free U and \bar{U} particles form bound systems at the impact parameter

$$a \approx (T/m)^{3/10} \cdot d_0. \tag{33}$$

The rate of such binding is then given by

$$\langle \sigma v \rangle = \pi a^2 v \approx \pi \cdot (m/T)^{9/10} \cdot \left(\frac{\alpha}{m}\right)^2 \approx \tag{34}$$

$$\approx 6 \cdot 10^{-13} \left(\frac{\alpha}{1/30}\right)^2 \left(\frac{300K}{T}\right)^{9/10} \left(\frac{250GeV}{m}\right)^{11/10} \frac{cm^3}{s}.$$

The successive evolution of this highly excited atom-like bound system is determined by the loss of angular momentum owing to γ -radiation. The time scale for the fall on the center in this bound system, resulting in $U\bar{U}$ recombination was estimated according to classical formula in [10]

$$\tau = \frac{a^3}{64\pi} \cdot \left(\frac{m}{\alpha}\right)^2 = \frac{\alpha}{64\pi} \cdot \left(\frac{m}{T}\right)^{21/10} \cdot \frac{1}{m} \quad (35)$$

$$\approx 4 \cdot 10^{-4} \left(\frac{300K}{T}\right)^{21/10} \left(\frac{m}{250GeV}\right)^{11/10} s.$$

As it is easily seen from Eq.(35) this time scale of $U\bar{U}$ recombination $\tau \ll m/T^2 \ll m_{Pl}/T^2$ turns to be much less than the cosmological time at which the bound system was formed.

Kinetic equation for U-particle abundance with the account of radiative capture on RD stage is given by Eq.(4). Its solution at $T_0 = T_f > T > T_{QCD} = T_1$, assuming in this period $g_{tot(s)} = const = g_f$ what allows to use transformation similar to Eq.(41), is given by

$$r_4 = \frac{r_0}{1 + r_0 \sqrt{\frac{\pi g_f}{45}} m_{Pl} \int_{T_1}^{T_0} \langle \sigma v \rangle dT} \approx \frac{r_0}{1 + r_0 \sqrt{\frac{20g_f \pi^3}{9}} \frac{\alpha^2 m_{Pl}}{m} \left(\frac{T_f}{m}\right)^{1/10}} \quad (36)$$

$$\approx 0.013 \left(\frac{m}{T_f}\right)^{1/10} \frac{m}{\alpha^2 m_{Pl}} \approx 4 \cdot 10^{-16} \frac{m}{250 \text{ GeV}} \left(\frac{30^{-1}}{\alpha}\right)^2,$$

where r_0 is given by Eq.(32).

At $T < T_{QCD}$ the solution for the effect of radiative recombination is given by

$$r_4 \approx \frac{r_0}{1 + r_0 \sqrt{\frac{20g_{QCD} \pi^3}{9}} \frac{\alpha^2 m_{Pl}}{m} \left(\frac{T_{QCD}}{m}\right)^{1/10}} \approx r_0 \quad (37)$$

with r_0 taken at $T = T_{QCD}$ equal to r_4 from Eqs.(9),(10) or (12).

Owing to more rapid cosmological expansion radiative capture of U -hadrons in expanding matter on MD stage is less effective, than on RD stage. So the result $r_4 \approx r_0$ holds on MD stage with even better precision, than on RD stage. Therefore radiative capture does not change the estimation of U -hadron pregalactic abundance, given by Eq.(9).

Appendix 3. Hadronization of U quarks

Here we show that in the baryon excessive background U quarks form U -baryons and \bar{U} form \bar{U} mesons, while the possible abundance of \bar{U} antibaryons and U mesons is suppressed exponentially. Indeed, even if the number density of \bar{U} -baryons, n_- , was initially comparable with the one of U -baryons, successive reactions with nucleons, such as

$$(\bar{U}\bar{u}\bar{u}) + N \rightarrow (\bar{U}u) + 2\pi \quad (38)$$

substantially reduce this number density down to a negligible value.

The decrease of relative \bar{U} -baryon abundance, $r_- = n_-/s$, is described by the equation

$$\frac{dr_-}{dt} = -r_- \cdot n_b \cdot \langle \sigma v \rangle. \quad (39)$$

Provided that total baryon number in Universe did not change significantly since QCD phase transition, nucleon number density n_b at the given time can be defined through the relation for baryon to entropy ratio r_b , which reads

$$\frac{n_b}{s} = r_b = const = \frac{n_{b\,mod}}{s_{mod}} = \frac{1}{7.04} \frac{n_{b\,mod}}{n_{\gamma\,mod}} \approx 10^{-10}. \quad (40)$$

At modern epoch the ratio $\eta_b = n_{b\,mod}/n_{\gamma\,mod} \approx 6 \cdot 10^{-10}$.

To solve equation Eq(39) we will use the transformation

$$-s \cdot dt = \sqrt{\frac{\pi g_{QCD}}{45}} m_{Pl} \cdot dT. \quad (41)$$

This transformation of differentials is applicable if the effective total number of degrees of freedom is approximately a constant during the most of temperature interval of considered period following the QCD phase transition, $g_{tot}(T < T_{QCD}) = g_{tot\,s}(T < T_{QCD}) = g_{QCD} \approx const$. Such a condition can be assumed to be fulfilled taking $g_{QCD} \approx 15$, which is a roughly averaged value over the most temperature interval after QCD transition. This value changes from about 17 to about 12 within 150MeV-200keV temperature interval and then virtually instantaneously it reduces down to the modern value, which is about 4. For our estimation we will take the cross section of such recombination as

$\sigma \sim \frac{1}{m_\pi^2} \cdot \frac{1}{v}$ and for rate of this reaction (6)

$$\langle \sigma v \rangle \sim \frac{1}{m_\pi^2} \approx 6 \cdot 10^{-16} \frac{\text{cm}^3}{\text{s}}.$$

Then one obtains the exponentially strong suppression of primordial \bar{U} -baryon abundance

$$r_- = r_0 \exp \left(- \int_{T_1}^{T_0} \frac{n_b}{s} \langle \sigma v \rangle \sqrt{\frac{\pi g_{QCD}}{45}} dT \right) \approx r_0 \exp \left(-0.15 \eta_b \frac{m_{Pl}}{m_\pi} \frac{T_0}{m_\pi} \right), \quad (42)$$

giving for $T_0 \sim T_{QCD}$ ($T_1 \ll T_0$)

$$r_- \sim r_0 \exp(-10^{10}).$$

Qualitatively the result does not change if we take more conservative estimation for the rate of this reaction (7). Substituting m_ρ instead of m_π in the Eq.(42) one obtains for $T_0 \sim T_{QCD}$

$$r_- \sim r_0 \exp(-4 \cdot 10^8).$$

The same exponential suppression takes place for $(U\bar{u})$ and $(U\bar{d})$ mesons. Therefore only U -baryons and \bar{U} -mesons should be considered as possible primordial forms of U -hadrons.

Similar suppression of U -hadrons with light valent antiquarks (\bar{u} and \bar{d}) should take place in any dense baryonic environment. In particular, it makes the lightest U baryon and \bar{U} meson the only possible forms of U -hadrons in terrestrial, solar or selenal matter.

At $T > T_w \approx 1\text{MeV}$ the rate of weak β -reactions exceeds the rate of cosmological expansion. Owing to these reactions and small mass difference of light u and d quarks one should expect comparable amounts of (Uuu) , (Uud) and (Udd) baryons (as well as of $(\bar{U}u)$ and $(\bar{U}d)$ mesons) in the Universe in the period $T_{QCD} > T > T_w$.

Low number density of U -hadrons makes negligible their role in reactions of Standard Big Bang Nucleosynthesis. In general one may discuss a bound deuteron-like state formed by the proton and $(\bar{U}u)$ meson in these reactions. However it looks unlikely that the interaction between the proton and this heavy 'meson' is strong enough to provide such a bound state.

Indeed, the deuteron is a weakly bound system which has a very small binding energy. In conventional proton-neutron potentials (see for example [8]) the

attraction between two nucleons is described mainly by the isoscalar exchange (such as σ -boson exchange). Therefore, assuming the additive quark model, we expect the proton- u -quark interaction to be 3 times smaller than that in deuteron. This is not enough to provide the existence of a bound state.

For the case of $p - \bar{u}$ -interaction the smallness may be partly compensated by the ω exchange which changes the sign interacting with the antiquark. Thus the situation with the possibility to form a $(U\bar{u}) + p$ bound state is not so evident. However, as it was discussed above, after QCD phase transition hadronic reactions such as

$$(U\bar{u}) + p \rightarrow (Uud) + \pi^0$$

should have resulted in exponential suppression of $(U\bar{u})$ -meson number density. Moreover, even being formed, $(U\bar{u}) + p$ state is unstable relative to this reaction.

Appendix 4. Hadronic recombination

In this Appendix we evaluate in different ways the cross section for formation of charmonium-like $(Q\bar{Q})$ -meson in collisions of hadrons, containing heavy quark Q and its antiquark \bar{Q} . We assume that such hadrons have initial kinetic energy $E \sim T$, where T is temperature. In the course of collision hadrons form "compound hadron", in which Q and \bar{Q} - quarks move with relative momentum k_{in} . Heavy quarks also possess y -attraction with a "fine structure constant" α_y .

In the formation of "compound hadron" y -attraction plays important role. One should take into account Sakharov enhancement in the cross section, which at $v/c \ll 1$ is reduced to $2\pi\alpha_y c/v$. It reminds the classical problem of accretion, when particle falls down the massive body of finite size (radius R) in its central potential. The well known cross section is $\sigma \sim 2\pi R(R + 2GM/v^2)$. In the case of y -attraction the corresponding expression reads $\sigma \sim 2\pi R(R + \alpha_y/T)$, with $R \sim 1/m_\pi$ given by the hadronic size.

Thanks to the y -attraction two colliding hadrons, one of which contains the Q quark and another one - the antiquark \bar{Q} , obtain the momenta $k_{in} \sim \sqrt{\alpha_y m_\pi m} \sim 1$ GeV even for very low T . Thus momentum of heavy quark inside compound hadron is determined by $T_{eff} = \max\{T, \alpha_y m_\pi\}$. For $T \leq m_\pi$ heavy hadron with momentum k_{in} crosses the compound hadron (of the size $R \sim 1/m_\pi$) very slowly (with $v \sim k_{in}/m$) at the timescale $t \sim (m/k_{in})(1/m_\pi)$, which is much larger than the hadronization timescale $t \sim (1/m_\pi)$. So, on one

side, relatively large momentum of heavy quarks gives us the possibility to neglect the effects of confinement, though, on the other side, the process is very slow and hadronization of light hadrons can play important role.

Since metastable hadrons of 4th generation are not discovered yet (and may be do not exist), there is evidently absent any direct experimental information about their interactions, and, in particular, about the cross section of reaction of hadronic recombination. Moreover, direct information on similar reaction for charmed and b-quark hadrons is also absent. It makes this question open for theoretical discussions and speculations. Such speculations, assuming formation of $(Q\bar{Q})$ -meson as a slow process of successive light hadron evaporation lead to the estimation of the order of (6) or (7) for the rate of hadronic recombination. The argument for such approach is that at low energy of colliding hadrons $T \leq m_\pi$, it is sufficient to emit few light hadrons (e.g. pions) from the compound hadron to bind Q and \bar{Q} within it and to prevent the disruption of compound hadron on (Qqq) and $(\bar{Q}q)$ states.

The more justified alternative approach is to take into account relatively large momentum of heavy quarks, to neglect effects of confinement and to consider the forming $(Q\bar{Q})$ meson as a small size hydrogen-like system. Such treatment can provide us realistic minimal estimation of the recombination rate. In this approach we can use the well known results for recombination of hydrogen atom with the replacement of electron mass m_e by the reduced mass $M = M_Q/2$ and the QED coupling α^{QED} by $\bar{\alpha} = C_F\alpha_s + \alpha_y \sim (4/3) \cdot 0.144 + 1/30 = 0.23$.

Here $C_F = (N_c^2 - 1)/2N_c = 4/3$ is the colour factor; the coupling α_s is evaluated at the distances r equal to the size of the ground state. For $M_Q = 250$ GeV this gives the binding energy $E_i = (M\bar{\alpha}^2)/(2i^2) = 3.2/i^2$ GeV ($E_1 = 3.2$ GeV for the ground state $i = 1$. The corresponding momentum $k_i = \sqrt{2ME_i} = 28/i$ GeV.)

In this approach the 'inclusive' reaction

$$(Qqq) + (\bar{Q}q) \rightarrow (Q\bar{Q}) + \dots(\text{anything}) \quad (43)$$

is considered as the recombination of the "free" heavy quarks

$$Q + \bar{Q} \rightarrow (Q\bar{Q}) \quad (44)$$

inside the "compound hadron". It is assumed that since the free quark recombination takes place at rather small distances, the influence on it of confinement and hadronization of light quarks, taking place at much larger distances with the probability equal to 1, can be neglected.

Now to evaluate the cross section we can use the known result for the electron-proton recombination

$$\sigma_{rec} = \sigma_r = \sum_i \frac{1}{N_c} \frac{8\pi}{3^{3/2}} \bar{\alpha}^3 \frac{e^4}{Mv^2 i^3} \frac{1}{(Mv^2/2 + I_i)} \quad (45)$$

where M and v are the reduced mass and velocity of Q -quark; I_i - ionization potential ($I_i = I_1/i^2$) [$I_1 = E_1 = 3.2$ GeV]. The colour factor $1/N_c = 1/3$ is the probability to find an appropriate anticolour.

To sum approximately over 'i' we note that $\sigma_r \propto 1/i$ for $I_i \gg Mv^2/2 = T_{eff}$ while at $I_i < T_{eff}$ the cross section $\sigma_i \propto 1/i^3$ falls down rapidly.

So effectively the sum goes up to $i = i_{max}$ with $i_{max} = \sqrt{3.2\text{GeV}/T_{eff}}$ corresponding to $I_{i_{max}} = T_{eff}$.

Thus the interpolation formula for recombination cross section reads:

$$\sigma_r = \left(\frac{2\pi}{3^{5/2}}\right) \cdot \frac{\bar{\alpha}^3}{T_{eff} \cdot I_1} \cdot \log\left(\frac{I_1}{T_{eff}}\right) = 1.8 \cdot \left(\frac{\log(I_1/T_{eff})}{T_{eff} \cdot I_1}\right) \text{mkbn} \cdot \text{GeV}^2 \quad (46)$$

and the recombination rate is given by

$$\langle \sigma v \rangle = \left(\frac{2\pi}{3^{5/2}}\right) \cdot \frac{\bar{\alpha}^3}{T_{eff} \cdot I_1} \cdot \log\left(\frac{I_1}{T_{eff}}\right) \cdot \frac{k_{in}}{M} \approx 0.4 \cdot (T_{eff} m^3)^{-1/2} (3 + \quad (47)$$

$$+ \log(T_{QCD}/T_{eff})) \approx 0.56 \cdot 10^{-20} \log(I_1/T_{eff}) \cdot \left(\frac{T_{QCD}}{T_{eff}}\right)^{1/2} \left(\frac{250\text{GeV}}{m}\right)^{3/2} \frac{\text{cm}^3}{s}.$$

This formula is valid in the interval of not too small $T_{eff} \gg m_\pi^2/2M$ (in order to neglect the confinement) and not too large $T_{eff} \ll I_1$ (at least $T_{eff} < I_1$).

For $T_{eff} = 4.7$ MeV (which corresponds to $k_{in} \sim 1.1$ GeV) it gives $\sigma_r = 0.8$ mb and $\langle \sigma v \rangle = 7 \text{mkbn} \cdot c \cdot (250\text{GeV}/m)^{3/2} = 2.1 \cdot 10^{-19} \left(\frac{250\text{GeV}}{m}\right)^{3/2} \frac{\text{cm}^3}{s}$.

Note that here we neglect the momentum of Q -quark inside the (Qqq) or $\bar{Q}q$ hadrons since this momentum $k \sim 0.3 - 0.5$ GeV is smaller than the incoming momentum $k_{in} > 1$ GeV, acquired in hadron collision due to y -attraction.

Appendix 5. Secondary U -hadrons from cosmic rays

Astrophysical mechanisms of particle acceleration lead to appearance of charged U -hadron component in cosmic rays. Neutral U -hadrons can not be acceler-

ated in this way directly, but their y -charge can make them to follow accelerated electrically charged U -particles. Primordial U -hadrons can be present in the interstellar gas, captured by Solar system. This primary flux of cosmic U -hadrons, falling down the Earth should enrich its U -hadron abundance.

Another source of such enrichment could be cosmic ray interaction with Earth's atmosphere. Let's estimate number of quarks of fourth generation that can be created in collisions of high energy cosmic protons with nuclei in the atmosphere of Earth. Assume for our estimation that high energy cosmic rays dominantly contain protons. To create pair of U -quark and its antiquark with mass m the c.m. energy

$$\sqrt{s} > 2m \quad (48)$$

is necessary.

In our case laboratory frame can be connected with Earth. Thus we can estimate c.m. energy of pair proton-nucleon as $s \approx 2m_p E_N$, where m_p is proton mass, E_N is the energy of incident nucleon. Then

$$E_N > E_{th} \approx \frac{2m^2}{m_p} \approx 1.3 \cdot 10^5 GeV. \quad (49)$$

Integral high energy proton flux depends on energy as [12]

$$I(E) = \begin{cases} E^{-1.7} (cm^2 \cdot s \cdot ster)^{-1}, & E < E_{knee}, \\ 3 \cdot 10^{-10} \cdot \left(\frac{E}{10^6 GeV}\right)^{-2.1} (cm^2 \cdot s \cdot ster)^{-1}, & E > E_{knee}, \end{cases} \quad (50)$$

where E_{knee} is about $3 \cdot 10^6 GeV$.

In the case of $m = 250$ GeV the expected inclusive cross section of U -hadron production in the proton-nucleon collision is of the order of 0.1 pb at E_N about $4.5 \cdot 10^6$ GeV and more than 1 pb at $E_N > 10^7$ GeV. To calculate the flux of U -hadrons in cosmic rays we have used the known leading order parton-parton cross sections of $gg \rightarrow Q\bar{Q}$ and $q\bar{q} \rightarrow Q\bar{Q}$ convoluted with the LO MRST2001 partons [26] and multiplied the result by the next-to-leading order K factor (of about 1.2) and by the mean atomic number of 'Air', $A_{atom} = 14.5$. The ratio of this cross section to the inelastic $p - Air$ cross section, parameterized in [23] was convoluted with the proton spectrum Eq.(50) (taken in differential form) and integrated over the incoming proton energy. This gives

$$I_U = 2.5 \cdot 10^{-21} (cm^2 \cdot s \cdot ster)^{-1}. \quad (51)$$

About half of the flux I_U comes from the region of $E_N > 12.5 \cdot 10^6$ GeV where the cross section $\sigma_U \geq 2$ pb. The major part of the produced heavy quarks after the hadronization forms the $U\bar{q}$ and $\bar{U}q$ mesons. The probability to form a baryon in the recombination with a light diquark is expected to be an order of magnitude smaller.

The estimated secondary flux of U -hadrons is by more than 12 orders of magnitude less, than the primary U -baryon component of cosmic rays if its fraction is given by Eq.(19).

The production and propagation of heavy hadrons, created by cosmic rays at $E_p > 1.3 \cdot 10^5 (\frac{m}{250 \text{ GeV}})^2$ GeV, will show itself as a long penetrating electromagnetic track, whose behaviour will be a combination of lepton-like and hadron-like shower.

Appendix 6. U -baryon atom pollution in Solar system

The y -charge neutrality condition holds neutral \bar{U} mesons near much less mobile U -baryon atoms in the slow sinking to the centers of planets. Representing the form of anomalous helium atoms U -baryon atoms are not chemically active and they should not form chemical compositions with matter, which might prevent them from sinking down the center.

Planet's gravity force on the surface is $F_g = mg$ and U -baryon atom of mass m sinks due to its action with velocity $V = \mu F_g$, where the mobility $\mu = mn\sigma v$ is determined by matter atom number density n and rate of multiple atomic collisions with matter σv . It gives

$$V = \frac{g}{n\sigma v}. \quad (52)$$

Taking for Moon $g = 1.6 \cdot 10^2 \text{ cm/s}^2$; $n = 6 \cdot 10^{23} / A \text{ cm}^{-3}$; $\sigma \sim 10^{-16} (m_a/m) \text{ cm}^2$, averaged atomic weight in selenal matter $A = m_a/m_p \approx 30$ and thermal velocity of atoms $v = 2 \cdot 10^4 (m/m_a)^{1/2} (T/300 \text{ K})^{1/2} \text{ cm/s}$, one obtains the velocity of sinking down the selenal surface $V \sim 10^{-8} (300 \text{ K}/T)^{1/2} \text{ cm/s}$.

Inside the homogeneous planet with matter density ρ at the radius R gravity force is $F_g = mG \frac{4\pi}{3} \rho R$. Then

$$V = \frac{4\pi}{3} \frac{Gm_a R}{\sigma v},$$

where m_a is the mass of planet matter atom, and the timescale of sinking

down the center of planet is given by

$$t = R/V = \frac{3}{4\pi} \frac{\sigma v}{Gm_a} = 6 \cdot 10^{16} \left(\frac{T}{300K} \right)^{1/2} s$$

independent of actual matter density and radius of planet. At internal temperature $T > 3000K$ this timescale exceeds the age of Solar system, what means that sinking can still continue in deep hot planet's interiors.

Taking for Moon the same flux (20) of U -hadrons falling down the Moon with interstellar gas and taking $j \sim \frac{4\pi I_U}{R}$ with $R \sim 10^8 cm$ being the Moon's radius one obtains from (24) the number density of U -hadrons in selenal matter $n \sim 0.3 cm^{-3}$.

In stars U -baryons should be dominantly ionized and the cross section of their collision in plasma does not differ much from such cross section for neutral \bar{U} -mesons. It strongly increases the velocity of U -hadron sinking and reduces the timescale of sinking down to stellar center. For Sun this timescale is $4 \cdot 10^9 (T/10^6 K)^{1/2} s$. With the account for the order of magnitude increase in Eq.(20) of velocity of gas, falling down the Sun, and taking for Sun $j \sim \frac{4\pi I_U}{R_\odot}$ with $R_\odot = 7 \cdot 10^{10} cm$ one obtains from Eq.(24) the number density of U -hadrons inside the Sun $n \sim 7 (T/10^6 K)^{1/2} cm^{-3}$. Note that the presence of doubly charged U -baryons in Solar corona could lead to anomalous He^+ lines, which can be hardly observable if there is no mechanism for local increase of U -baryon abundance.

Effects of Solar wind and Solar activity prevent interstellar gas from falling down the Sun reducing Solar abundance of U -baryons. At the distance R from Sun such effects decrease as $\propto R^{-1/2}$.

Heliopause at the border of Solar system, where solar wind stops pushing out infalling gas, may provide a shield, preventing interstellar gas penetration in Solar System. Provided that this shielding is sufficiently effective, anomalous helium coming with interstellar gas can be stopped in heliopause, and the effects of its pollution of Earth's matter can strongly decrease.

Appendix 7. Effects of Q -hadron recombination in matter

Within the effective thickness of atmosphere-Ocean layers or within the sinking depth equilibrium between U -hadron income and recombination is established. In the result of recombination, which takes place homogeneously in all the regions occupied by U hadrons, rest energy of U -quarks converts into the energy of ordinary hadrons. The latter (dominantly π and K mesons) should in their turn give rise to photons and neutrinos as their decay products. Total

hadronic energy release in recombination corresponds to $2mI_U$ with energy of ordinary hadrons $E < m$. For I_U given by Eq.(20) and $m = 250\text{GeV}$ it is by order of magnitude smaller than the hadronic energy released in Earth's atmosphere and ground by cosmic rays.

Moreover, the dense matter is opaque for charged pions and kaons originated from $U\bar{U}$ recombination. For charged pions with energy $E \sim 10\text{GeV}$ the rate of their absorption in water

$$\Gamma_i = n \langle \sigma v \rangle \approx 4 \cdot 10^8 1/s$$

is by 3 orders of magnitude higher, than their decay rate

$$\Gamma_d = \frac{m_\pi}{E} \frac{1}{\tau_\pi} \approx 5 \cdot 10^5 1/s.$$

It leads to strong absorption of charged pions and to corresponding suppression ($\sim \Gamma_d/\Gamma_i$) of neutrino fluxes from their decay. Such fluxes would be still larger than the effect of $U\bar{U}$ recombination in atmosphere, in which it is much stronger suppressed by the factor $\propto (n_{atm}/n_w)^2 \sim 10^{-6}$, where n_{atm} and n_w are respectively atomic number densities in air and water.

Neutral pions can dominantly escape absorption, but deep layers of water are opaque for gamma radiation from their decay, reducing the observable gamma source to a surface layer of thickness about l_γ , mean free path of γ in water. All the Earth is however transparent for neutrino with energy $E \leq m = 250\text{GeV}$.

So the stationary regime of $U\bar{U}$ recombination in Earth should be accompanied by the neutrino flux and by the gamma radiation from the Ocean surface. The calculation of these fluxes is valid for the general case of any choice for lightest Q -quark and Q hadrons, what we reflect in notations below.

The mean multiplicities of ν and γ produced in the $Q\bar{Q}$ recombination at rest were evaluated using the JETSET 7.4 Monte Carlo code [24]. We neglect the spin-spin interaction and assume that just due to statistics 25% of the $U\bar{U}$ pairs are in the pseudoscalar (0^-) state, and thus mainly decay onto the two gluon jets, while 75% of pairs are in the 1^- state and decay onto the three gluon jets. The results are presented in Table 1 where we show the total multiplicities of gamma and electron, muon and τ neutrinos for the case of $m = 250$ GeV. To give some impression about the energy distributions we present also the multiplicities of particles with the energy $E > 0.1, 1, 10$ and 100 GeV. Besides this in Table 1 we show the energy fractions carried by the gamma and electron, muon and τ neutrinos as well. Note that the numbers for $E > 100$ GeV had in our calculations a low statistical significance and are shown just to demonstrate the strong suppression of the fluxes at high energies. Moreover all the numbers corresponds to the $Q\bar{Q}$ annihilation in

vacuum and do not account for the attenuation caused by the absorption of high energy pions in medium (Earth or Ocean).

The last effect is crucial for the neutrinos produced via the charged pion decay. The lifetime of a fast pion is proportional to the Lorenz gamma factor E/m_π and grows with energy. The density of nucleons in the Earth is about $n = 1.5 \cdot 10^{24} \text{ cm}^{-3}$, the cross section of π absorption $\sigma(\pi N) \approx 20 \text{ mb} = 2 \cdot 10^{-26} \text{ cm}^2$. So the mean free path of pions is $l = 1/(n\sigma) = 30 \text{ cm}$. On the other hand the decay length for charged pions $c \cdot \tau = 780 \text{ cm} \cdot (E/m_\pi)$. Thus the suppression is $l/(c\tau) = (30 \cdot 140 \text{ MeV}/780)/E_\pi = 5.4 \text{ MeV}/E_\pi$. Strictly speaking $E_\nu < E_\pi$ (so we can expect a stronger than $5 \text{ MeV}/E_\nu$ suppression) On the other hand after the interaction the fast pion does not disappear completely; it creates few pions of a lower energy (due to this reason the suppression should be not so strong) These two factors approximately compensate each other. So the final estimate $5 \text{ MeV}/E_\nu$ looks reasonable.

Therefore in the Earth the yield of fast neutrinos will be additionally suppressed by the factor of about $5 \text{ MeV}/E_\nu$. However the prompt neutrinos, coming mainly from the decay of charmed particles, are not suppressed by this effect. To demonstrate the role of prompt neutrinos for each sort of neutrinos in the right columns of Table 1 we present the multiplicities (and corresponding energy fractions) calculated in the limit when the charged pions, kaons and μ -mesons are stable. For a high energies exceeding few GeV the flux of prompt neutrinos give the dominant contribution.

	γ	$\nu_e + \bar{\nu}_e$		$\nu_\mu + \bar{\nu}_\mu$		$\nu_\tau + \bar{\nu}_\tau$	
N_{total}	69	62	0.095	124	0.091	0.02	0.019
$N(E > 0.1 \text{ GeV})$	62	47	0.094	97	0.090	0.02	0.019
$N(E > 1 \text{ GeV})$	28	14.4	0.080	31	0.077	0.017	0.016
$N(E > 10 \text{ GeV})$	2.4	0.61	0.028	1.5	0.027	0.0057	0.0057
$N(E > 100 \text{ GeV})$	0.001	0.0004	0.00017	0.0004	0.00010	0.0003	0.000
Energy fraction	0.27	0.12	0.0018	0.26	0.0017	0.0004	0.00035

Table 1

Multiplicities of γ , electron-, muon- and τ - neutrinos produced in the recombination of $(Q\bar{Q})$ pair with $m = 250 \text{ GeV}$. First line shows the total multiplicities while the next 4 lines correspond to multiplicities of particles with the energies $E > 0.1, 1, 10, 100 \text{ GeV}$ (in the $(Q\bar{Q})$ pair rest frame). The last line presents the energy fraction carried by each sort. For each sort of neutrinos numbers in the left and right columns correspond to all neutrinos (produced in the result of fragmentation and decays of all annihilating products in vacuum) and to only prompt neutrinos respectively.

In particular, the stationary regime of $Q\bar{Q}$ recombination in Earth should be accompanied by gamma radiation with the flux $F(E) = N(E)I_U l_\gamma / L$,

where energy dependence of multiplicity $N(E)$ of γ quanta with energy E is demonstrated in table 1, and l_γ is the mean free path of such γ quanta. At $E > 100 \text{ MeV}$ one obtains the flux $F(E > 100 \text{ MeV}) \sim 3 \cdot 10^{-9} \frac{f_4}{10^{-10}} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1}$, coming from the surface layer $l_\gamma \sim 10^2 \text{ cm}$.

One should also expect neutrino flux from $Q\bar{Q}$ recombination in Earth with spectrum given in table. At $E_\nu > 1 \text{ GeV}$ it corresponds to the flux $\sim 2 \cdot 10^{-8} \frac{f_4}{10^{-10}} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1}$.

Appendix 8. Upgoing muon signal from $U\bar{U}$ annihilation in atmosphere

Here we consider the stationary regime of equilibrium between the incoming interstellar gas pollution and $U\bar{U}$ annihilation in matter and discuss the possibility to detect the upgoing muon signal from such annihilation in atmosphere.

Assuming an infalling flux, given by Eq.(20) $I_U \approx 1.5 \cdot 10^{-7} \frac{f_4}{10^{-10}} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1}$, we must observe a tiny component of annihilation in air ($\sim 10^{-3}$ as the ratio of atmospheric column height to Ocean's depth). Effects of this annihilation will be mostly masked by a more abundant downward cosmic ray showering.

Nethertheless the presence of a tiny upgoing muons, tracking from $U\bar{U} \rightarrow \text{hadrons} \rightarrow \pi^\pm \rightarrow \mu^\pm$ chains, is the source of an "anomalous" upgoing muon flux. Its value may exceed

$$I_{\mu\uparrow} = N(E_\mu > 1 \text{ GeV}) I_U = 4.6 \cdot 10^{-9} \frac{f_4}{10^{-10}} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1}.$$

This flux is not easy to observe on the ground, but it may be observable from mountain, airplane or balloons.

Indeed, μ trace in air exceeds 6 km its flux estimated above is already comparable with the albedo muon flux, observed at 93° - 94° in NEVOD-DECOR experiment [27]. Its detection may be easily tested. It may be exceeding 3-4 orders of magnitude the upgoing muons from atmospheric ν_μ ($I_\mu \sim (2 - 3) \cdot 10^{-13} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1}$).

Even $E_\mu > 10 \text{ GeV}$ harder spectra may play an important role. The expected flux is $I(E_\mu > 10 \text{ GeV}) \geq 2 \cdot 10^{-10} \frac{f_4}{10^{-10}} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1}$ with negligible pollution by downward cosmic ray secondaries bent by geomagnetic fields.

These signals could be complementary or even dominant over the expected upgoing one from τ airshowers due to $\text{UHE}\nu$, skimming the Earth's crust [28,29,30,31].

Appendix 9. Metastable Q -hadrons

Interaction of cosmic rays with the spectrum (50) with the matter in disc with averaged number density $n \sim n_g \sim 1 \text{ cm}^{-3}$ for the inclusive cross section of U -baryon production taken as in Appendix 5 results during the lifetime of galactic cosmic rays $T_{cr} \sim 10^7 \text{ yr}$ in the creation of integral cosmic ray flux of U baryons

$$I_U \approx n \sigma_{Ub} c T_{cr} I(E \geq E_{th}) \approx 4 \cdot 10^{-22} (\text{cm}^2 \cdot \text{s} \cdot \text{ster})^{-1}, \quad (53)$$

being one order of magnitude smaller than the flux (51) of U -hadrons produced in the cosmic ray interaction with Earth's atmosphere. This flux is several orders of magnitude below the level of sensitivity expected in future cosmic ray experiments, in particular in AMS 02. For such low incoming flux as (51) the number density of anomalous helium stored in Earth during its age is $n \sim 4 \cdot 10^{-12} \text{ cm}^{-3}$, which corresponds to such a low recombination rate that kinetic equilibrium is not established and equilibrium solution (24) is not valid. The anomalous helium abundance in this case does not exceed $r \approx 4 \cdot 10^{-35}$, what is 16 orders of magnitude below the existing upper limits. It makes in the case $\tau < t_U$ the search for anomalous helium at accelerators most promising.

The above estimations of primordial abundance of U -baryons and of their production rate by cosmic rays are also valid for the case, when the lightest U -baryon is isosinglet (Uud)-state with the electric charge $+1$. However, in this case the conclusions differ drastically from the case of double charged baryon, since (Uud)-baryon represents the form of anomalous hydrogen. Mass spectrometry was used on a variety of light elements [14], [17], [18], [19], and achieved the lowest limit $\sim 10^{-30}$ on hydrogen isotopic abundance at around 100 GeV. These experimental constrains are by more than 11 orders of magnitude stronger, than for anomalous helium. These constrains exclude the case of such U -baryon with $\tau > t_U$, but in the case $\tau < t_U$ the experimental upper limits can be satisfied, since the abundance of anomalous hydrogen produced interaction of cosmic rays in atmosphere and stored in Earth is in this case about $r \approx 4 \cdot 10^{-35} \frac{\tau}{t_U}$. For a very wide range of $\tau < t_U$ this lifetime is sufficiently large to prevent the U -baryon decay in detectors, making (meta-)stable U -baryons a profound signature for 4th generation quarks in accelerator searches.

If particles are sufficiently longliving to survive to the period of galaxy formation t_{gal} , their annihilation can take place and the EGRET constraint on this annihilation is valid. For $\tau < t_{gal}$ such annihilation can not take place and the astrophysical effects of decay should be considered. These effects depend on the decay modes, but even for the significant fraction of electromagnetic and hadronic cascades among the decay products, effects of U -hadron decay

in CMB spectrum, electromagnetic backgrounds and light element abundance are consistent with observational constraints (see for review [32] and [33]) for the cases A and B and for a wide range of lifetimes in the case C. In particular, for maximal fraction of electromagnetic energy release (~ 0.5) one obtains from [33] the constraint $f_4 < 5 \cdot 10^{-9}(1 + z_d)$, so that even case C is possible for the decay redshift $z_d > 400$, corresponding to the lifetime $\tau < 5 \cdot 10^{13} s$.

Similar arguments are valid for the case, when D -quark is lighter than U -quark, and $+1$ charged (Duu) and ($\bar{D}u$) are the lightest D -hadrons. Such hadrons can hardly form nuclear bound states with $Z > 1$ and thus cause the problem of anomalous hydrogen overproduction, if D -quark lifetime exceeds the age of the Universe.

On the other hand, though the current quark mass relation is $m_d > m_u$, it is not excluded that the self-energy induced by the QED interaction can compensate the mass difference ($m_d - m_u$), making the electrically neutral ($\bar{D}d$) the lightest \bar{D} -hadron. If in the same time the lightest D -baryon is also the neutral (Dud), and the lightest D -hadrons are not bound with hydrogen nuclei in anomalous isotopes of hydrogen, primordial D -hadrons would represent an interesting form of strongly interacting dark matter particles. Having only nuclear interaction with the matter, such particles decouple from plasma at the temperatures below $T_d \sim 30$ keV, and then on MD stage, participating the development of gravitational instability are dominantly distributed in the halo of galaxies.

After decoupling particle velocity decreases inversely proportionally to the scale factor, i.e. as $\propto T$. In this case the rate of radiative binding has the form

$$\langle \sigma v \rangle = \pi a^2 v \approx \pi \cdot (m/T_d)^{9/10} \cdot \left(\frac{\alpha}{m}\right)^2 \left(\frac{T_d}{T}\right)^{9/5} \quad (54)$$

and at $T_{RD} = T_0 < T < T_d = T_1$ solution (36) of the kinetic equation (4) is given by

$$\begin{aligned} r_4 &= \frac{r_0}{1 + r_0 \sqrt{\frac{\pi g_f}{45}} m_{Pl} \int_{T_1}^{T_0} \langle \sigma v \rangle dT} \approx \\ &\approx \frac{r_0}{1 + r_0 \frac{\sqrt{5g_f \pi^3}}{12} \frac{\alpha^2 m_{Pl}}{m} \left(\frac{T_c}{m}\right)^{1/10} \left(\frac{T_c}{T_{RD}}\right)^{4/5}}. \end{aligned} \quad (55)$$

Here $g_f = g_{tot s mod} = 43/11$ and r_0 is given by (9) in case A, (10) in case B or (12) in the case C. In the cases A and B the primordial abundance practically does not change, while in the case C the Q -hadron abundance is reduced to the end of RD stage by a factor of 10. The energy release, related

with the reduction of Q -hadron abundance in the case C, is consistent with the constraints on the distortions of CMB spectrum, but hadronic cascades from annihilation products can interact with primordial ^4He and pollute the primordial light element composition by excessive ^6Li , ^7Li and ^7Be [34] (see review in [33]).

Indeed, following [33], hadronic jet from gluon with energy E_g , originated from $Q\bar{Q}$ annihilation, contains $N_{\bar{p}} \leq \frac{1}{7}N_\pi \leq \frac{1}{7}(E_g/1\text{GeV})^{1/2}$ pairs of p and \bar{p} with averaged energy $E_{\bar{p}} \sim (E_g/1\text{GeV})^{1/2}$. The chain of nuclear reactions with energetic ^3He , T, D products of $p(\bar{p})$ induced destruction of primordial ^4He yields [34]

$$\frac{\Delta n_{^6\text{Li}}}{n_b} = (E_{\bar{p}}/1\text{GeV})^{2/3} N_{\bar{p}} \sim 30 \cdot 2.5 \cdot 10^{-6} f_4,$$

which should not exceed the observed ^6Li abundance $\frac{n_{^6\text{Li}}}{n_b} \sim 10^{-10}$. It restricts the relative amount f_4 of annihilated $Q\bar{Q}$ as $f_4 < 1.3 \cdot 10^{-6}$, what excludes the possibility of $Q\bar{Q}$ annihilation on late RD stage in the case C (for which $f_4 = 2 \cdot 10^{-6}$). Detailed analysis of nucleosynthesis by hadronic cascade, similar to the considered recently in [35] would only strengthen this restriction.

On the MD stage at $T_{RD} > T$ before the period of galaxy formation the rate of radiative binding in nearly homogeneously expanding matter retains the form (54), but the transformation (41) has now the form

$$-s \cdot dt = \sqrt{\frac{\pi g_{QCD}}{45}} m_{Pl} \sqrt{\frac{T}{T_{RD}}} \cdot dT. \quad (56)$$

It leads to the solution of the kinetic equation (4) at $T_{RD} = T_0 > T > T_{gal} = T_1$ given by

$$\begin{aligned} r_4 &= \frac{r_0}{1 + r_0 \sqrt{\frac{\pi g_f}{45}} m_{Pl} \int_{T_1}^{T_0} \langle \sigma v \rangle \sqrt{\frac{T}{T_{RD}}} dT} \approx \\ &\approx \frac{r_0}{1 + r_0 \frac{\sqrt{20 g_f \pi^3}}{9} \frac{\alpha^2 m_{Pl}}{m} \left(\frac{T_c}{m}\right)^{1/10} \left(\frac{T_c}{T_{RD}}\right)^{4/5} \left(\frac{T_{RD}}{T_1}\right)^{3/10}}. \end{aligned} \quad (57)$$

So on MD stage to the period of galaxy formation at $T_{gal} = T_{CMB} \cdot (1 + z_{gal}) \sim 20 T_{CMB}$ for $T_{RD} = T_{CMB} \cdot (1 + z_{RD}) \sim 2 \cdot 10^4 T_{CMB}$ (where $T_{CMB} = 2.7\text{K}$ is the modern temperature of CMB) Q -hadron abundance in the case C should decrease by additional factor of 20, making its pregalactic abundance about $r_4 \sim 10^{-8}$. Such Q -hadron annihilation on the MD stage not only leads to energy release close to the constraints on CMB spectrum distortions, but also

results in the γ background incompatible with the EGRET data. Thus in the case C the considered neutral Q -hadrons should be unstable with the lifetime, less than 10^{15} s. Note that for the cases A and B, which are not excluded by the above arguments, owing to high peculiar velocity effects of Q -hadron annihilation in Galaxy are strongly reduced.

Finally, an interesting case of the lightest (Ddd)-baryon with electric -1 charge can be mentioned. At the temperatures about tens keV such baryons can bind with protons and helium nuclei in atom-like systems. The $((Ddd)+p)$ -system with the size of $\sim 3 \cdot 10^{-12}$ cm can hardly have atomic cross section for its interaction with matter. As for the $((Ddd)+\text{He})$ -system its recombination with electrons makes it to follow atomic matter in the period of galaxy formation. Specific properties of these systems may provide them to be elusive for the existing methods of anomalous hydrogen searches. However, this case is not supported by the mass ratios of current quarks or by the arguments of quark model.

Following the additive quark model arguments one can not expect the deuterium-like state to be formed by $(\bar{D}d)$ with protons. The potential of $(\bar{D}d)$ -nucleon interaction is expected to be about 3 times smaller than that for $p-n$ interaction.

For the case of (Dud) -nucleon interaction the potential is about $2/3$ of the $p-n$ potential and the factor $(2/3)$ is not enough to make definite conclusion. The problem is that the effective reduced mass M_{eff} is in this case twice larger than that for $p-n$ system, while the true parameter is not the potential $V(r)$ but the magnitude $V(r) \cdot M_{eff}$. So, following the arguments of the Additive Quark Model neutral $(Dud)n$ or $+1$ charged "nuclear" states $(Dud)p$ are not excluded and most probably should exist. Their existence would exclude D -quark with lifetime exceeding the age of the Universe, even if in the course Standard BBN reactions they dominantly transform into $Z > 1$ states, since such transformation can hardly reduce the abundance of $Z = +1$ states by 15 orders of magnitude, what is necessary to escape the problem of anomalous hydrogen overproduction. So D -quarks with lifetime less than the age of the Universe, being hardly eligible to searches for anomalous isotopes in the matter and in cosmic rays, can become a challenge for accelerator search.

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